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Systematic Review

Integrating Building- and Site-Specific and Generic Fragility Curves into Seismic Risk Assessment: A PRISMA-Based Analysis of Methodologies and Applications

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Abstract: Fragility curves are fundamental tools in seismic risk assessments, providing insights into the vulnerability of structures to earthquake-induced damages. These curves, which plot the probability of a structure reaching or exceeding various damage states against earthquake intensity, are critical for developing effective modification strategies. This review aims to present the characteristics between building- and site-specific fragility curves, which incorporate detailed local characteristics, and generic fragility curves that apply broader, more generalized parameters. We utilize the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to systematically review the literature to address key research questions about the methodological differences, applications, and implications of these curve types in assessing seismic risks. The methods involved a comprehensive search and combination of existing studies on the topic, focusing on how these curves are developed and applied in real-world scenarios. The results from this review show that building- and site-specific curves, while more precise, require extensive data and are therefore more complex and costly to develop. In contrast, generic curves, though less accurate, offer a cost-effective solution for preliminary risk assessments over large areas. The conclusions drawn from this review suggest that while each type has its merits, the choice between building- and site-specific and generic fragility curves should be guided by the specific requirements of the seismic risk assessment task, including available resources and the need for precision in the vulnerability estimations.

Keywords: fragility curves; site-specific fragility curves; building-specific fragility curves; generic fragility curves; risk-targeted seismic design; seismic vulnerability assessment

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1. Introduction

A fragility curve is a graphical representation that shows the probability of a structure experiencing different levels of damage or performance deterioration at varying intensities of ground shaking. It is a crucial tool in seismic risk assessment, aiding in understanding a structure's vulnerability to earthquakes. Fragility curves are developed by relating the probability of exceeding a specific damage state to the severity of ground shaking, typically using metrics such as peak ground acceleration or spectral acceleration. These curves help in predicting potential damage during earthquakes, prioritizing structural interventions, and guiding risk mitigation efforts [1–5]. The versatility of fragility curves makes them applicable across various types of structures, including residential buildings, bridges, historical monuments, and critical infrastructures.

Building on the concept of fragility curves, the Performance-Based Earthquake Engineering (PBEE) framework offers a more comprehensive approach to seismic risk assessments. PBEE not only accounts for the likelihood of various damage states as depicted by fragility curves but also integrates additional layers of analysis to evaluate broader impacts. The PBEE framework is a methodology used for the seismic risk assessment of buildings, providing valuable metrics like collapse hazard, economic losses, downtime, casualties, and environmental impacts [6]. Fundamentally, PBEE connects engineering demand parameters (EDPs) such as inter-story drift with decision variables (DVs) such as repair costs and safety impacts, allowing for a full lifecycle assessment of a building's seismic performance. PBEE involves steps such as defining the seismic demand, structural capacity, damage assessment based on engineering demand parameters (EDPs) and intensity measures (IMs) and estimating economic losses due to potential damages [7]. Fragility curves play an essential role in PBEE, representing the probability of exceeding damage states based on seismic hazard levels, with various methods available for their calculation, including empirical, moment, and probabilistic models [8]. The PBEE equation is as follows:

$$\lambda_{DV} = \iiint G_{DV|DM}\, dG_{DM|EDP}\, dG_{EDP|IM}\, d\lambda(IM) \tag{1}$$

where the triple integral sign ($\int\int\int$) expresses the conditional probabilities across different levels of intensity measure (IM) (e.g., spectral and peak ground acceleration, spectral velocity), engineering demand parameters (EDPs) (e.g., inter-story drift or floor acceleration), and damage measures (DMs) (e.g., condition assessment, necessary repairs, cracks, buckling) to compute the overall risk (λ) in terms of decision variables (DVs). Basically, this equation integrates over all possible seismic events (characterized by IMs), their effects on the structure (EDPs), the resulting damage (DMs), and finally, the implications of that damage in terms of decision variables like cost, safety, and functionality (DVs).

This allows us to calculate the expected annual loss or other decision variables by integrating the chain of probabilities from a seismic hazard to structural response, damage, and consequences [6,9–12]. It forms the mathematical foundation for making informed decisions about building design, retrofitting, and land-use planning based on the probabilistic assessment of seismic risks.

Fragility curves in PBEE are lognormal functions defining structural behavior based on an intensity measure (IM), offering insights into possible damages due to seismic actions and uncertainties [13]:

$$P(IM = \alpha) = \Phi\left[\frac{\ln(\alpha) - \mu}{\beta}\right] \tag{2}$$

where $P(IM = \alpha)$ is the probability of a collapse given the intensity measure, "α" represents a capacity measure (e.g., spectral acceleration), "μ" is the mean (or median) of the natural logarithm of the intensity measure at which a collapse is expected to occur, "β" is the logarithmic standard deviation (reflecting the uncertainty or variability in the capacity measure) and "Φ" is the cumulative distribution function (CDF) of the standard normal distribution.

Recent advancements in seismic fragility curves have highlighted a range of innovative approaches and methodologies aimed at improving the assessment and management of seismic risks for various structures, from state-based approaches [14,15], machine learning techniques [16,17] (e.g., artificial neural network (ANN) [18,19]), empirical methods [20–22] (e.g., the Bayesian method [23,24], statistical approaches and model transformations [25,26], direct analysis techniques [27,28]), and analytical modeling [29–32] (e.g., equivalent SDOF models and disaggregation [33], high-dimensional model representation and Monte-Carlo simulations [34], mechanical-based assessments and retrofit intervention [35], an analysis modeled after specific codes [36]) to assess and enhance the seismic resilience of buildings and infrastructures.

Key insights include the evaluation of seismic safety margins [37], the application of innovative fragility curve development techniques [14,38–41], and the implementation of computational models to reduce efforts while maintaining accuracy [18,19]. Researchers have focused on the seismic performance of both conventional reinforced concrete and steel structures [42,43], as well as specialized assessments for historical buildings and essential facilities [29,35,39], highlighting the wide applicability and importance of updated fragility assessments in earthquake engineering. These contributions significantly aid in risk mitigation strategies [16,44], improve predictive models [19,24], and support the structural integrity assessments necessary for minimizing earthquake-induced damages [25,27].

The purpose of this review is to enhance the understanding of fragility curves, focusing particularly on explaining the differences between building- and site-specific and generic fragility curves. Utilizing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method, this study aims to systematically answer research questions that explore the details, applications, and implications of these two distinct types of fragility curves in seismic risk assessment. This comprehensive analysis will help in identifying the strengths, weaknesses, and appropriate contexts for the application of each curve type, contributing to more informed and effective seismic risk management strategies.

2. Methodology

A PRISMA systematic methodology was employed to review the existing literature, ensuring the novelty of the work. PRISMA consists of a 27-item checklist and a four-phase flow diagram. The checklist outlines essential items for ensuring the transparent and comprehensive reporting of a systematic review [45,46]. This included defining research questions (RQs) to construct the review, identifying key terms for the database searches, and filtering relevant articles. In the next step, the screening phase, titles and abstracts of the identified papers are reviewed, and irrelevant articles are excluded. Following this, the eligibility phase, a full review of the remaining articles is conducted to ensure they fit within the scope of the review, with non-relevant studies being further excluded. Finally, the selected articles are thoroughly examined, and the data are interpreted for inclusion in the review process [47]. The review paper selection process, from identification through screening to final inclusion, is summarized in Figure 1.

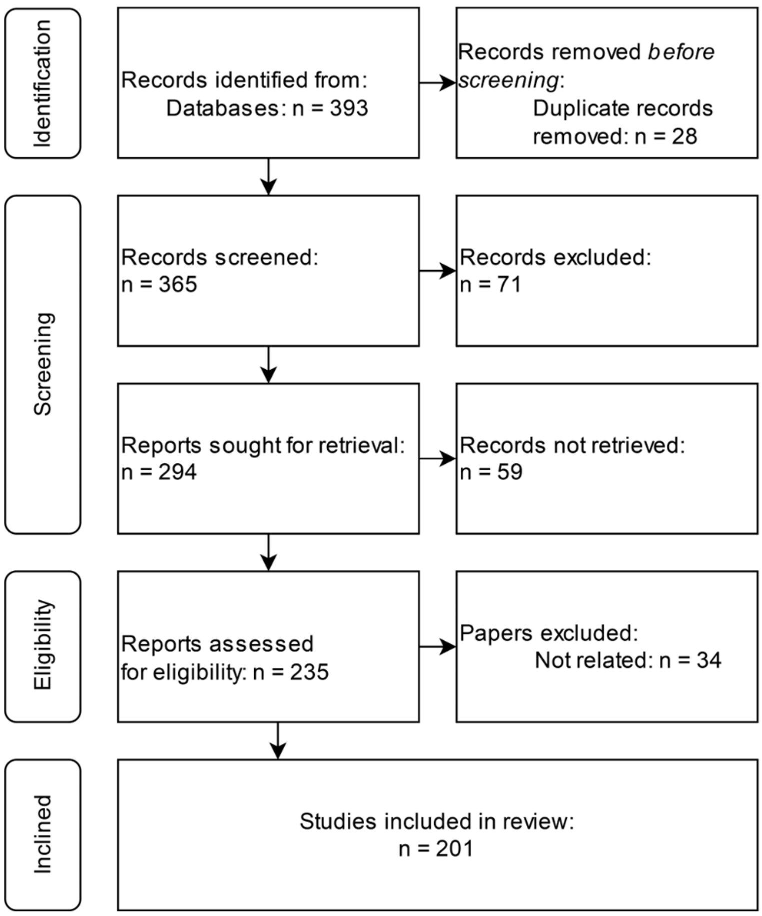

Figure 1. The PRISMA diagram for this systematic review.

2.1. Significance of Study

Despite the growing interest and state-of-the-art publications in the field of fragility curves, there is still no unified systematic method, specifically using the PRISMA methodology, for reviewing the existing literature comprehensively. This gap makes it more difficult to identify research gaps and suggest novel areas of future research foundations. This study addresses this gap by conducting a thorough review across various publication types (e.g., journal articles, conference papers). By doing so, it aims to chart the progress in this area and facilitate further advancements.

In this review, a fragility curve is defined as the use of advanced probabilistic models to quantify the likelihood of a structure exceeding or reaching various states of damage under seismic loading. A fragility curve leverages different methodologies to enhance seismic vulnerability assessments by integrating building- and site-specific characteristics (e.g., local seismic activity, soil properties) and building details, while a generic approach represents the probability of a structure or a class of structures reaching or exceeding various states of damage under seismic loading, without taking into account building- and site-specific characteristics.

The scope of this systematic review investigates fragility curves, examining both building- and site-specific and generic approaches. It covers studies on the advantages and disadvantages of each method, contextualized within the framework of building risk targeting. It includes studies involving automated tools in any of the stages of data gathering, screening, and analysis. Studies not meeting these criteria are excluded.

2.2. Construction of Research Questions

After defining the scope, establishing RQs that are formulated serves as the foundation of this study. These questions simplify the process of gathering related articles and evaluating the related literature. Three main RQs are established, two of which are accompanied by a follow-up question/s to construct this research systematically:

1. How do building- and site-specific fragility curves, developed through PSHA-based record selection for generic SDoF systems, enhance seismic risk assessments compared to generic fragility approaches?
    a. What are the primary advantages of utilizing PSHA-based record selection in developing building- and site-specific fragility curves for diverse structural types?
    b. How does the specificity of data input in site-specific fragility curves impact the accuracy and reliability of seismic vulnerability assessments?
2. In what scenarios are generic fragility curves, which disregard building- and site-specific characteristics beyond the fundamental period and design intensity, preferred in seismic risk management?
    a. What are the inherent benefits of using generic fragility curves on a large scale?
3. How do practitioners balance the simplicity and broader applicability of generic fragility curves with the need for precise risk assessments in critical infrastructure?

2.3. Identification of Keywords, Collection and Preprocessing of Articles

Using the construction of RQs, keywords are then identified. The keywords include "fragility curves", "site-specific fragility curves", "building-specific fragility curves", "generic fragility curves", "risk-targeted seismic design", "seismic vulnerability assessment", "seismic" and "building". Following the identification of key terms, a search was conducted on different search engines, primarily utilizing various databases including Hindawi, ScienceDirect, Google Scholar, Multidisciplinary Digital Publishing Institute (MDPI) and Scopus. Using these keywords help to comprehensively capture the broadness of research on the development, application, and implications of both building- and site-specific and generic fragility curves in this review. We utilized ResearchGate to compile an initial list of relevant conference papers due to its extensive repository and ease of access to author-uploaded content. Following this, we verified and cross-referenced these papers using Google Scholar, a more widely recognized and credited source. This approach ensured a comprehensive and credible literature review, incorporating a broad range of relevant studies and maintaining the integrity of the review.

In Table 1, the results of the database search are summarized, showing the number of publications retrieved and those considered relevant for the review. The database searches yielded a total of 393 publications. After removing 17 duplicates and excluding 71 studies, 59 publications could not be retrieved. Subsequently, a filtering process segregated the publications into those to be considered and those not relevant to the review, resulting in 201 and 34 publications, respectively. Figure 2 illustrates the breakdown of articles based on type and year.

Table 1. Numbers of results of publication on databases.

Databases	Number of Results	Considered Papers
Hindawi	3	2
ScienceDirect	50	19
Google Scholar	199	84
MDPI	72	34
Scopus	69	61
TOTAL	393	201

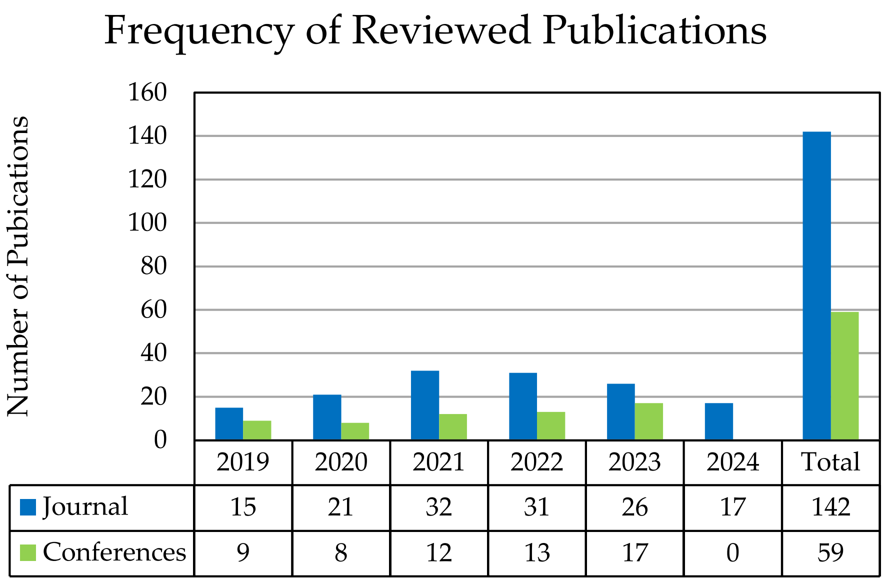

Figure 2. Frequency of reviewed publications over the past five (5) years in terms of types and years.

3. RQ1. How Do Building- and Site-Specific Fragility Curves, Developed Through PSHA-Based Record Selection for Generic SDoF Systems, Enhance Seismic Risk Assessments Compared to Generic Fragility Approaches?

Building-specific and site-specific fragility curves serve distinct but complementary purposes in assessing structural vulnerability to earthquakes [3]. Building- and site-specific fragility curves, developed through Probabilistic Seismic Hazard Analysis (PSHA)-based record selection for generic Single Degree of Freedom (SDoF) systems [48,49], offer a refined approach to seismic risk assessments that significantly enhances their accuracy and effectiveness compared to generic fragility approaches [50,51]. These site-specific fragility curves begin with a detailed analysis of seismic hazards specific to a particular site or region [52,53]. This involves using PSHA to identify and evaluate potential earthquake scenarios that could affect the site, considering factors such as earthquake magnitude, frequency, and distance from seismic sources [9,54]. The PSHA process also includes a consideration of local soil conditions and their impact on seismic wave propagation, which can greatly affect ground motion characteristics at the site [13,53].

In Figure 3, the process and application of developing building- and site-specific fragility curves are illustrated. This figure highlights the steps involved, from detailed analysis of seismic hazards specific to the site or region to the prioritization of high-risk buildings and sites for mitigation. Recent studies have highlighted the importance of incorporating various hazard models and structural conditions in fragility curve development. Kim et al. [55] investigated the effects of earthquake characteristics on the fragility of nuclear power plant (NPP) concrete containments, finding that local seismic characteristics significantly impact structural vulnerability. Similarly, López-Castañeda et al. [56] demonstrated that strong motion duration and local soil profiles play a critical role in the nonlinear response of buildings, further emphasizing the necessity of site-specific data.

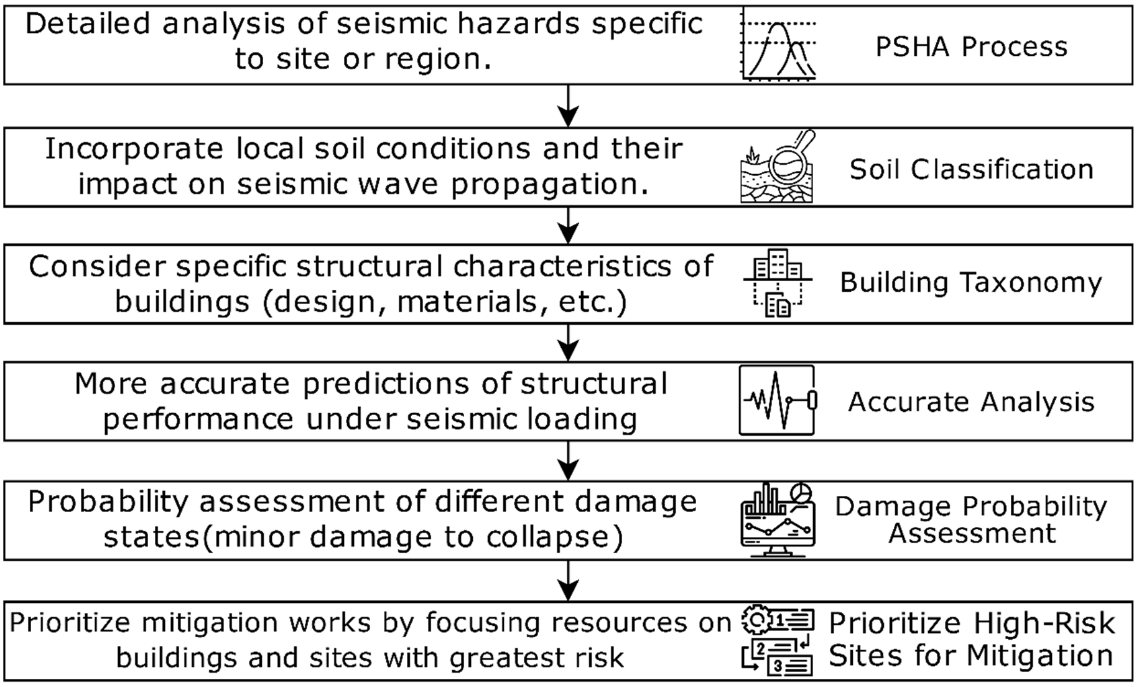

Figure 3. Process and application of developing building- and site-specific fragility curves.

Site-specific fragility curves provide a more accurate representation of the seismic demand on structures by incorporating detailed and localized hazard assessments [57,58]. Tools like the US Geological Survey's ShakeMap, which provides site-specific shaking metrics and uncertainties for forensic and engineering purposes, contribute significantly to the development of fragility curves and loss model calibration [59]. ShakeMap's real-time data, used for post-earthquake damage assessments and engineering analyses, offer an essential layer of precision for retrofitting and other decision-making activities in seismic risk management. They consider not only the intensity of ground shaking expected but also how these ground motions interact with the specific structural characteristics of buildings at the site [60]. This includes accounting for the building's design, materials, and construction quality, all of which influence how a structure will respond during an earthquake [54,61]. Liu et al. [62] proposed a clustering-based framework for selecting ground motions, ensuring the collapse fragility estimation for SDoF systems converges accurately with fewer records, which streamlines the fragility curve development process.

This high level of specificity in site-specific fragility curves allows for more accurate predictions of structural performance under seismic loading [42,52]. Studies by Mubarak and Kumar [63] presented a physics-based approach for assessing the seismic vulnerability of railway embankments, illustrating the importance of accounting for site-specific ground motions and soil conditions. Further, Mathews et al. [64] explored the effects of soil–structure interaction (SSI) on mid-rise RC buildings, showing a significant increase in fragility with soft soil conditions.

Fragility curves also enable engineers and risk assessors to determine the probability of different damage states for a specific building, from minor damage through to complete collapse, based on the unique combination of a seismic hazard and building vulnerability at that location [57,65–67]. Park et al. [68] studied site-specific fracture risk, underlining how variations in building materials and local conditions influence vulnerability assessments. Additionally, the probabilistic framework developed by Ranjbaran et al. [69] for generic fragility curves validated the relevance of tailoring fragility models to site conditions, particularly in cases of extreme hazard scenarios.

This designed assessment helps in prioritizing mitigation works, such as retrofitting or strengthening measures, more effectively by focusing resources on buildings and sites with the greatest risk [70–72]. Taherian and Kalantari [73] investigated the risk-targeting approach to ground motion selection, showing how integrating site-specific fragility data can optimize seismic retrofitting efforts in high-risk regions. In contrast, generic fragility curves apply a broader approach. They typically use generalized assumptions about building types and seismic conditions that do not account for local variations in seismic hazard or structural properties [74]. This method is useful for large-scale or preliminary assessments where detailed data may not be available, or when a quick, broad overview of risk is required [75]. However, the trade-off is a lower accuracy in risk predictions, which can lead to either overestimations or underestimations of actual structural vulnerabilities. Such inaccuracies can result in either unnecessary spending on over-conservative designs or, conversely, an underestimation of structures that are more vulnerable than estimated [6,75]. Vargas-Alzate et al. [76] further elucidated this by demonstrating that generic fragility curves fail to capture site-specific variations in seismic intensity measures, leading to skewed risk assessments.

3.1. Precision and Reliability

Building- and site-specific fragility curves provide higher precision in estimating seismic risk by considering the unique features of each building and its site. These curves offer substantial advantages over generic approaches by incorporating detailed information on local seismicity, soil conditions, and structural characteristics, thereby improving reliability in seismic risk assessments.

For instance, studies have demonstrated the importance of incorporating site-specific seismic hazard data derived from PSHA in fragility curve development. These site-specific adjustments allow the curves to account for regional seismicity variations, thus providing a more tailored assessment of seismic demand and potential building response under earthquakes [55,77]. In addition, the integration of empirical data from recent earthquakes provides real-world validation, reinforcing the accuracy of building-specific fragility curves. The empirical validation process aligns modeled fragility estimates with observed damage patterns, thereby increasing confidence in risk mitigation strategies [78]. Fragility curves can also benefit from continuous updates using data from Structural Health Monitoring (SHM) systems, enabling real-time risk assessments that adapt to structural condition changes over time [79].

Moreover, building-specific fragility curves support economic assessments by enabling detailed cost–benefit analyses for retrofitting, seismic upgrades, and insurance calculations. These assessments optimize resource allocation by prioritizing retrofitting efforts for buildings with the highest seismic risk, thus ensuring that mitigation strategies are both cost-effective and technically sound [80,81].

The framework extends beyond individual buildings to include critical infrastructure systems like power stations and bridges, allowing a more holistic view of community resilience. This broader application supports urban planning by identifying high-risk areas and prioritizing resources where they are most needed [82,83]. Additionally, the ability to incorporate advanced numerical modeling techniques ensures that complex interactions between structural elements and seismic forces are accurately simulated, further enhancing the precision of these assessments [84].

Finally, considering the impacts of climate change on seismic risks, especially in coastal areas, is becoming increasingly important. Fragility curves adapted for climate-induced environmental changes, such as flooding and sea level rise, provide a forward-looking approach to risk management [85,86]. This evolving methodology ensures that fragility assessments remain relevant and effective in future seismic events. In Table 2, the benefits and precision of building- and site-specific fragility curves in enhancing seismic risk assessments are summarized.

Table 2. Highlights of the benefits and precision of building- and site-specific fragility curves in enhancing seismic risk assessments.

Aspect	Description	Citation
Site-Specific Adjustments	Building- and site-specific curves incorporate local seismicity, soil conditions, and building characteristics, leading to more accurate assessments.	[43,87]
Consideration of SSI Effects	Site-specific curves consider soil–structure interaction (SSI), which significantly impacts the seismic response of buildings.	[88,89]
Enhanced Risk Mitigation	Detailed fragility curves support better informed decision-making for risk mitigation and retrofitting strategies.	[90,91]
Performance-Based Design	This entails a performance-based seismic design, ensuring buildings meet specific safety and functionality criteria during earthquakes.	[92,93]
Empirical Validation	Empirical data from recent earthquakes are used to validate and refine fragility curves, increasing their accuracy.	[94]
Integration with SHM	This combines Structural Health Monitoring (SHM) data to continuously update and improve fragility curves.	[95,96]
Economic Assessments	This facilitates detailed cost–benefit analyses for seismic upgrades and insurance purposes.	[97,98]
Assessment of Non-Structural Components	This includes non-structural components in the analysis, providing a comprehensive view of potential damages.	[99,100]
Urban Planning	This supports urban planning and development by identifying high-risk areas and prioritizing resources.	[101,102]
Advanced Modeling Techniques	This uses advanced numerical modeling techniques to simulate complex interactions between structural elements and seismic forces.	[103,104]
Adapting to Climate Change	This assesses the impact of climate change on seismic risk, particularly in coastal and flood-prone areas.	[105–107]
Infrastructure Systems	This extends the assessment to include critical infrastructure systems, enhancing community resilience.	[108]
Historical Data Utilization	This incorporates historical earthquake data to refine hazard models and improve predictive capabilities.	[109–111]

3.2. Case Studies and Practical Applications

Numerous case studies demonstrate the practical applications and benefits of building- and site-specific fragility curves. These case studies highlight how this approach can lead to more accurate and reliable seismic risk assessments, which are essential for informed decision-making in earthquake-prone areas.

For instance, Fosoul and Tait [112] developed fragility curves for a multi-span isolated bridge in Eastern Canada, comparing its as-built condition with a retrofitted version using Unbonded Fiber Reinforced Elastomeric Isolators (U-FREIs). The results demonstrated that the U-FREI system significantly reduced seismic demands, enhancing the bridge's resilience during earthquakes. This case underscores the importance of retrofitting strategies and how site-specific adjustments can dramatically alter structural performance under seismic loading. Similarly, Fotopoulou et al. [113] explored the application of building-specific fragility curves for reinforced concrete school buildings in Thessaloniki, Greece, contrasting these with generic fragility curves. The study found that building-specific curves provided a more accurate reflection of the vulnerabilities, emphasizing the need for localized fragility analysis in critical structures. This reinforces the argument that site-specific fragility curves, tailored to a building's characteristics and local seismicity, offer more precise risk assessments than generalized models. Another study by Altindal et al. [114] applied a site-specific probabilistic seismic risk assessment to an urban center in Istanbul. This approach incorporated localized hazard curves and building-specific fragility models for old masonry and reinforced concrete buildings, revealing urgent retrofitting needs for vulnerable structures in the city. This case study illustrates the critical role of fragility curves in regional risk mitigation strategies, particularly for densely populated, historically significant urban areas. Additionally, Waenpracha et al. [115] developed fragility curves for reinforced concrete buildings subjected to tsunami loading in Thailand, accounting for masonry-infilled walls. The study highlighted how site-specific hazard models and building configurations dramatically influence the vulnerability of structures in coastal regions. This case emphasizes the importance of integrating multiple hazard types, such as earthquakes and tsunamis, into fragility curve development. Rosas et al. [116] provided a case study on bridges built on soft soils in Mexico City, employing site-specific numerically derived fragility curves to assess seismic vulnerability under three-dimensional seismic environments. This study illustrated how soil conditions and ground motion characteristics influence the structural response and fragility of critical infrastructure. Finally, Ghods and Rofooei [117] introduced a holistic record selection method for site-dependent structural response estimation, using bagging algorithms to streamline fragility curve development for steel moment-resisting frames across multiple sites. The approach reduced the computational effort while maintaining accuracy, demonstrating how innovative modeling techniques can improve site-specific seismic assessments.

Building on these case studies, a framework for implementing site-specific fragility curves can be derived. The process begins with a site-specific seismic hazard analysis (PSHA) to capture localized ground motion characteristics [118,119]. Next, detailed building information, including design, materials, and structural performance, is incorporated [120,121]. Numerical simulations (e.g., incremental dynamic analysis) are used to develop fragility curves based on varying intensity measures [122,123]. Empirical validation through past earthquake data and continuous updates via Structural Health Monitoring (SHM) enhance the precision of these models [124,125]. The framework ends in applying these refined fragility curves to prioritize retrofitting and mitigation strategies, ensuring resource allocation is focused on the most vulnerable structures [126]. An example application of this framework can be demonstrated using the Thessaloniki school buildings case study [113]. The framework begins with a site-specific hazard analysis, followed by the development of fragility curves tailored to the specific vulnerabilities of each building typology. These curves then inform retrofitting strategies aimed at enhancing the seismic resilience of the school infrastructure. In Table 3, specific examples are highlighted, covering different types of infrastructure and addressing unique seismic risk factors for each. These case studies illustrate how tailored fragility assessments can improve retrofitting and resilience strategies, ensuring the protection of critical infrastructure and minimizing potential losses in high-risk areas.

Table 3. Various case studies demonstrating the practical applications and benefits of building- and site-specific fragility curves.

Aspect	Description	Citation
Seismic Risk Assessment of Substations	Seismic risk assessment of a low-voltage substation, highlighting significant impact of maintenance conditions on seismic risk.	[127]
Masonry-Infilled RC Frames	Performance-based seismic evaluation and design for masonry-infilled RC frames using an extensive database of experimental tests.	[128]
Seismic Reliability of Italian RC Frames	Seismic reliability maps for reinforced concrete frames in Italy, showing hazard-dependent safety levels.	[129]
Seismic Fragility of Curved Bridge Piers	Fragility curves for curved reinforced concrete bridge piers considering short- and long-period earthquakes.	[130]
Water Distribution Systems	Seismic resilience evaluation of urban water distribution systems considering soil corrosive environments.	[131]
Seismic Risk of Electric Network	Assessment of seismic risk for elements of electric network in Romania, highlighting impact of component anchoring.	[132]
Seismic Risk in School Buildings	Seismic risk assessment of RC frame school buildings in Sri Lanka, demonstrating increased damage probabilities with building height.	[133]
Mitigation of Critical Infrastructure Risk	Probabilistic methodology for seismic risk mitigation of critical infrastructures using risk mitigation to investment ratio (RMIR).	[127]
Seismic Risk of Infrastructure Systems	Comprehensive framework for seismic risk assessment of infrastructure systems, focusing on uncertainties and interdependencies.	[108,134,135]
Seismic Fragility of Ports	System-wide seismic risk assessment of port facilities, incorporating ground shaking and liquefaction effects.	[102]

3.3. RQ1.a. What Are the Primary Advantages of Utilizing PSHA-Based Record Selection in Developing Building- and Site-Specific Fragility Curves for Diverse Structural Types?

Utilizing PSHA-based record selection in developing building- and site-specific fragility curves brings numerous advantages, particularly in terms of enhancing the accuracy and relevance of seismic risk assessments across diverse structural types. This methodological approach allows for a deep, refined understanding of the seismic hazards specific to a location, which is important in making the fragility curves relevant to the actual conditions a structure might face during an earthquake [52,136].

The process of creating highly accurate and relevant seismic fragility curves for diverse structural types, as illustrated in Figure 4, begins with conducting a PSHA-based record selection. This method rigorously analyzes potential seismic events that could affect a site, considering various seismic sources and their characteristics such as location, magnitude, and frequency of occurrence [10,13,53]. This process involves generating a suite of ground motion records that represent the range of possible seismic impacts on a particular site, based on detailed geological and seismological data [137,138]. The selection of these records is critical as it ensures that the seismic inputs used in developing fragility curves reflect realistic scenarios, thus making the resulting curves highly applicable and specific to the site and building being assessed [138,139].

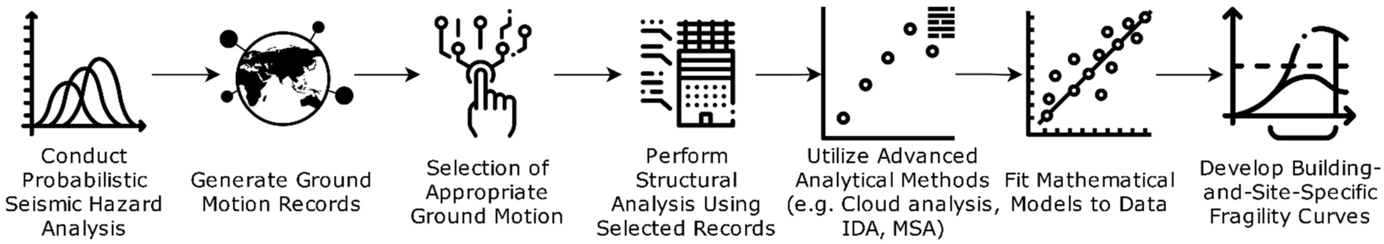

Figure 4. Process of creating highly accurate and relevant seismic fragility curves for diverse structural types through PSHA-based record selection.

This specificity is particularly beneficial when assessing the seismic vulnerability of diverse structural types, from high-rise buildings and bridges to industrial facilities and residential houses [140,141]. Each type of structure responds differently to seismic forces depending on factors like design, materials, height, and construction quality [61]. By using PSHA-based record selection, the fragility curves can accurately incorporate these variabilities [142], providing risk assessments that are fitted to the specific characteristics and vulnerabilities of each structure type [52,66].

Moreover, the introduction of methods like Cloud Analysis, Incremental Dynamic Analysis (IDA), and Multiple-Stripe Analysis (MSA) further refines the process [143–147]. Cloud Analysis, for instance, involves plotting a cloud of points that represent the responses of a structure under various seismic intensities, providing a visual and analytical method to understand structural behaviors under different earthquake scenarios [144]. This approach helps in identifying trends and outliers in the structural response, enhancing the robustness of the fragility assessment [13,48]. Incremental Dynamic Analysis is another powerful tool that systematically increases the intensity of seismic input to a structure to observe its response at various levels of intensity [148–150]. This method provides detailed insights into the progressive damage states of the structure, facilitating the development of more detailed and accurate fragility curves [74]. Multiple-Stripe Analysis complements these techniques by evaluating the structure under multiple levels of seismic intensity, defined by different stripes on a hazard curve [146,151]. This method ensures that the fragility curves are not only based on a single prediction of peak ground acceleration but consider a range of possible scenarios, which enhances the comprehensiveness and reliability of the seismic risk assessment [144,152].

In seismic fragility analysis, a fitting-based approach involves using statistical methods to fit a mathematical model to the data obtained from Incremental Dynamic Analysis (IDA) and Multiple-Strip Analysis (MSA) [145,153]. By fitting mathematical models to the data points collected during these (IDA and MSA) analyses, researchers can derive fragility curves that depict the structural vulnerability at different seismic intensity levels. The fitting-based approach in IDA and MSA allows researchers to accurately model the relationship between seismic intensity and structural response. It becomes possible to quantify the likelihood of damage or failure under various seismic scenarios, aiding in resilience assessments by fitting curves to the data [50,154].

Summaries of the primary methodologies used in seismic fragility analysis—Cloud Analysis, Incremental Dynamic Analysis (IDA), Multiple-Stripe Analysis (MSA), and the fitting-based approach—along with the key academic citations that discuss their application and effectiveness as seen in Figure 5. Each methodology is associated with specific studies that contribute to the understanding of structural responses under seismic conditions, enhancing the development of more accurate and robust fragility curves.

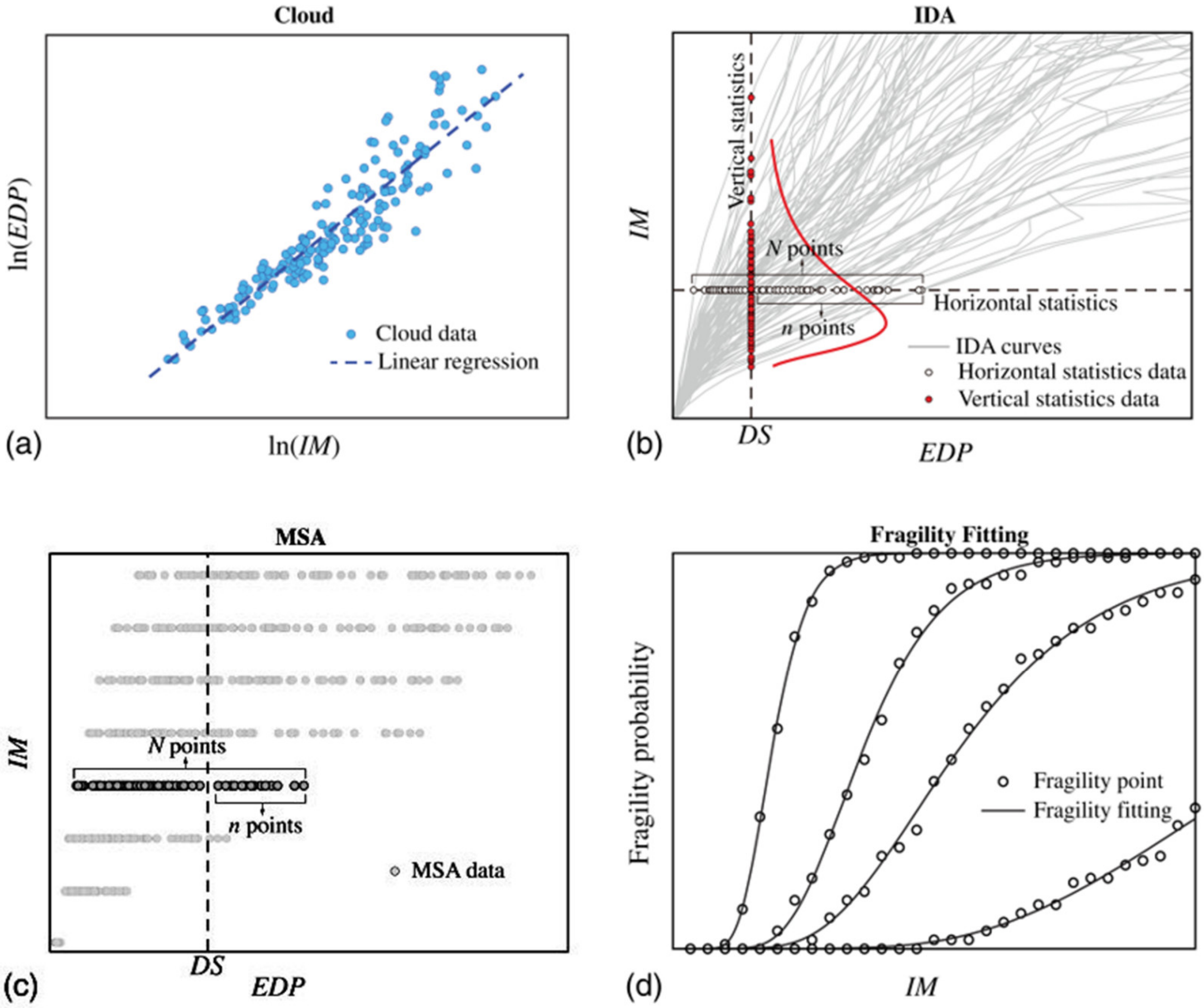

Figure 5. Pang and Wang [50] illustration of fragility modeling: (**a**) using logarithmic linear regression to relate intensity measure (IM) to engineering demand parameters (EDPs) in Cloud; (**b**) employing IDA curves to estimate damage probabilities in two distinct approaches; (**c**) utilizing MSA data to forecast damage probabilities; and (**d**) developing fragility curves based on fitting methods in both IDA and MSA. (Reprinted with permission from Ref. [50], 2021, ASCE).

Together, these advanced analytical methods—enhanced by the accuracy of PSHA-based record selection—offer robust frameworks for developing fragility curves that are deeply informed by both the probabilistic nature of seismic hazards and the specific seismic response characteristics of different building types [48,136]. This combination not only improves the precision of seismic vulnerability assessments but also supports more effective seismic design [141], retrofitting strategies [155], and emergency preparedness plans [65,70], ensuring that structural interventions are both scientifically grounded and practically viable [156]. Table 4 provides an overview of the methodologies and techniques utilized in seismic fragility analysis, categorizing them by specific methods, descriptions, and key citations. These methodologies offer unique approaches to assess and develop fragility curves for various structural types and seismic conditions.

Table 4. Overview of methodologies and citations in seismic fragility analysis.

Method	Description	Citation
Cloud Analysis	Analyzed the role of infill panels and floor systems in RC buildings and assessed the seismic vulnerability of RC buildings designed for gravity loads using cloud-based probabilistic seismic fragility estimation and nonlinear dynamic analyses.	[8,36,157]
	Utilized cloud-based machine learning techniques and applied ANN techniques on cloud to derive fragility curves for RC frames and a 3D industrial frame, incorporating uncertainty analysis and comparing results with MSA.	[16,19]
	Developed fragility curves for single-story steel buildings using cloud-based 3D nonlinear finite element models and investigated critical connections in steel frames using cloud-based collapse fragility curves and nonlinear time history analyses.	[27,41]
Incremental Dynamic Analysis	Assesses the collapse probability and seismic performance of RC buildings using IDA and AIDA methods, with a focus on modeling uncertainty and collapse sensitivity to ground motion suites.	[158–160]
	Evaluates the seismic performance of mid-rise CLT and smart buildings equipped with SMA connections using IDA, highlighting their drift control, residual deformation, and fragility under seismic loads.	[4,161,162]
	Investigates the fragility of regular and irregular steel structures equipped with BRBs using nonlinear IDA and analyzes the seismic performance of RC masonry and dual-system buildings in high-seismic zones.	[149,163,164]
	Analyzes the seismic performance and fragility of base-isolated RC structures under near-fault pulse-type ground motions and asymmetric frame buildings with various eccentricities.	[144,150]
	Assesses seismic vulnerability and develops fragility curves for historic masonry buildings, school buildings, and various RC buildings using probabilistic and HAZUS methodologies.	[74,145,148]
Multiple Stripe Analysis (MSA)	Proposes a framework for assessing seismic risk including the development of seismic risk maps and risk reduction programs and evaluates typology-specific fragility curves for seismic demand maps in low-seismicity regions.	[52,70]
	Investigates the effect of building response on the fragility of freestanding symmetric or asymmetric contents using MSA and quantifies fragility function uncertainty in infilled RC frame buildings.	[75,146]
	Discusses the conversion of fragility curves between different intensity measures to ensure consistency with seismic hazards and assesses the seismic fragility of single-story RC precast buildings considering multiple fragility methods.	[13,151]
	Presents a modified intensity measure to improve accuracy in fragility analysis of structural systems and explores the role of local building typologies in regional vulnerability and risk assessment.	[65,152]
	Assesses the effectiveness of retrofitting techniques for Peruvian confined masonry dwellings using fragility functions and compares different seismic fragility analysis methods, highlighting the sensitivity of fragility estimates.	[154,165]
	Proposes an efficient method for converting fragility curves from cloud analysis to IDA and MSA and investigates the generation of new fragility curves for common building types in Iran using empirical and statistical approaches.	[50,166]
Fitting-Based Analysis	Evaluates the impact of slab thickness on RC buildings using fragility curves and conducts a fragility analysis of lightweight steel drywall partitions based on experimental data.	[167,168]
	Analyzes the influence of soil–structure interaction on the seismic fragility of RC buildings using double-parameter damage models and investigates the seismic fragility of jacket-type offshore structures.	[142,169]
	Develops fragility curves for RC flat slab buildings with and without infill and investigates the impact of various parameters on seismic fragility using pushover analysis and HAZUS methodology.	[167,170]

3.4. RQ1.b. How Does the Specificity of Data Input in Site-Specific Fragility Curves Impact the Accuracy and Reliability of Seismic Vulnerability Assessments?

The specificity of data input in site-specific fragility curves significantly impacts the accuracy and reliability of seismic vulnerability assessments by directly affecting the definition of fragility functions and consequently the seismic risk evaluations for structures. As illustrated in Figure 6, the specificity of data inputs plays a critical role in enhancing the accuracy and reliability of site-specific fragility assessments. This figure presents an overview of the process, highlighting key components such as input data specificity, vulnerability assessment factors, and comprehensive damage assessment. It is noted that variations in the fragility curve functions for different structural typologies support the hypothesis that single definitions may not be suitable for ensuring a uniform collapse risk, highlighting the importance of typology-specific fragility curves [52,58,72]. For example, a study by Donà et al. [171] introduced a mechanics-based model for developing fragility curves specific to Italian masonry buildings, emphasizing how typology-specific definitions can improve the accuracy of seismic vulnerability assessments. Similarly, Bernardo et al. [172] discussed the importance of ambient vibration testing and how incorporating real-world data into fragility analysis leads to more reliable results for masonry structures.

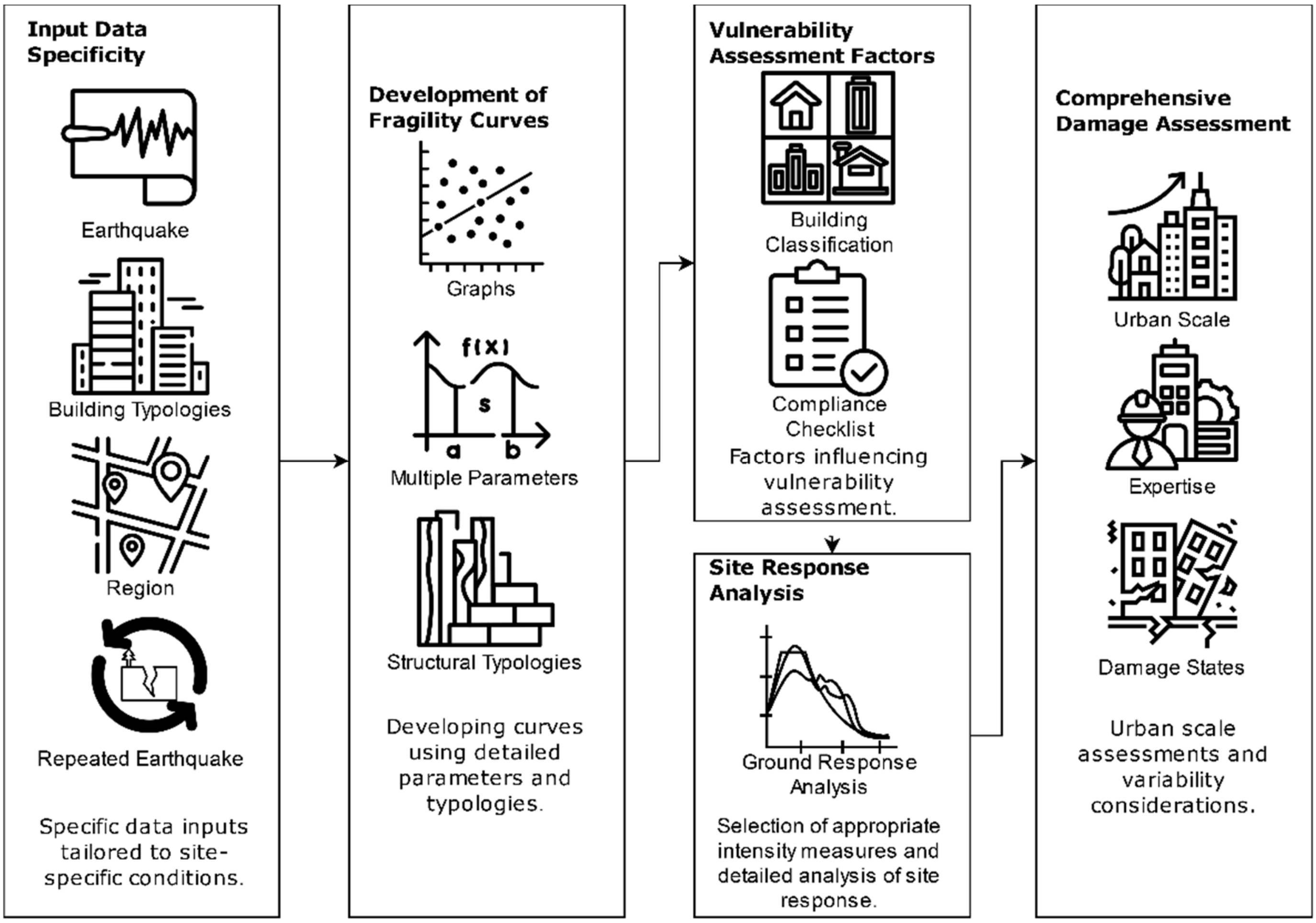

Figure 6. Impact of data specificity on the accuracy and reliability of site-specific fragility curves.

Additionally, in regions of low seismicity, the inherent capacity of structures not designed with seismic considerations significantly influences the outcomes of the risk-targeted PGA maps [9,12]. For instance, Baltzopoulos et al. [173] examined how the use of behavior factor-based design methods in low-hazard regions resulted in different levels of seismic risk for buildings, reinforcing the need for tailored fragility curves in such contexts.

As for repeated earthquakes, the development and use of fragility curves or surfaces become an efficient tool to assess the seismic risk due to the cumulative damage that can occur [74,139]. Fragility curves traditionally rely on single parameters such as peak ground acceleration (PGA), but for a more accurate assessment of seismic effects, a fragility surface considering multiple parameters can provide a more precise study [49,52,141].

Another aspect affecting the reliability of fragility curves is the correlation between seismic input and expected damage, described by an analytical function where the mean damage increases with macro-seismic intensity and depends on the vulnerability index, which varies according to building typology and other factors [3,65]. Alawneh et al. [174] explored this aspect by assessing the seismic fragility of levee relief wells during flooding, using random forest regression models to develop fragility curves, illustrating the importance of accounting for specific structural features. By properly classifying buildings based on material, number of stories, and construction age, and then coupling this process with seismic regulation compliance, a more accurate vulnerability index can be assigned [66,136].

It is also suggested that comprehensive damage assessments using fragility curves at an urban scale are reasonable despite the difficulty of perfect accuracy due to complexities such as the detector's expertise and varying damage states [61]. Furthermore, the choice of seismic intensity measure is a crucial factor that influences the estimation of fragility curves, indicating the necessity of selecting appropriate intensity measures for accurate vulnerability analysis [138,152,175]. Cicek and Sarı [176] demonstrated this by utilizing Monte Carlo simulations to analyze fragility curves for data centers, highlighting how different intensity measures impact fragility curve generation.

Additionally, a more detailed site response analysis can lead to differences in damage distribution and thus influence the outcome of fragility assessments, particularly for certain types of structures like masonry and reinforced concrete [10]. These data suggests a relationship between the comprehensiveness of the site response analysis and the resulting accuracy of the fragility curves in predicting damage [139,177]. A recent study by de Silva [178] underscored the critical role of soil–structure interaction on site-specific seismic demand, showing how this interaction significantly alters fragility curve predictions for masonry towers. Similarly, Batikh et al. [179] incorporated seismic aftershocks into multi-hazard PRA frameworks for nuclear facilities, providing a more detailed fragility assessment by accounting for time-dependent variables.

Table 5 provides details on how different parameters and analytical considerations in the development and application of fragility curves influence the accuracy and reliability of seismic vulnerability assessments. Each aspect contributes distinct insights into the complexities of modeling seismic risk, highlighting the need for comprehensive, nuanced approaches in fragility curve analysis.

Table 5. Key parameters and their impact on seismic fragility curve analysis.

Aspect	Description	Citation
Typology-specific fragility curves	Variations in fragility functions for different structural typologies highlight the need for tailored approaches to ensure accurate risk evaluations.	[52,58,72]
Inherent capacity in low seismicity regions	The inherent structural capacity significantly impacts seismic risk assessments in areas not primarily designed for seismic activity.	[9,12,173]
Cumulative damage from repeated earthquakes	The use of fragility curves or surfaces to assess cumulative damage from repeated seismic events enhances risk evaluation.	[74,139]
Fragility surfaces	A fragility surface that considers multiple parameters offers a more accurate assessment of seismic effects than traditional single-parameter models.	[49,52,141]

Table 5. *Cont.*

Aspect	Description	Citation
Correlation between seismic input and damage	The analytical function linking seismic input with expected damage varies by the vulnerability index, which depends on building typology among other factors.	[3,65,174]
Building classification for vulnerability indexing	Classifying buildings by material, story number, and age, and coupling this with compliance to seismic regulations, allows for a more precise vulnerability indexing.	[136,157,171]
Urban scale fragility assessments	Comprehensive damage assessments at the urban scale are feasible and valuable, though challenging due to the complexity and variability in damage states.	[61,172]
Choice of seismic intensity measure	Selecting appropriate seismic intensity measures is crucial for estimating accurate fragility curves.	[152,175,176]
Site response analysis	Detailed site response analysis influences damage distribution and the accuracy of fragility curves, particularly for specific structure types like masonry and reinforced concrete.	[139,177,178]

4. RQ2. In What Scenarios Are Generic Fragility Curves, Which Disregard Building- and Site-Specific Characteristics Beyond the Fundamental Period and Design Intensity, Preferred in Seismic Risk Management?

Generic fragility curves, which focus primarily on generalized characteristics like the fundamental period and design intensity [49,52], are preferred in several seismic risk management scenarios due to their broader applicability and ease of use [3,175]. Figure 7 illustrates various scenarios where generic fragility curves are preferred in seismic risk management. One such scenario is during preliminary risk assessments where detailed data are not available or when a swift overview is necessary [65,66]. For instance, in emergency management and rapid response planning, generic curves provide quick estimates of potential building damages across a wide area [61,136], allowing for the efficient allocation of resources and immediate response actions. A study by Odabasi et al. [180] demonstrates that such approaches are particularly effective in high-population areas such as Istanbul, where tall buildings must be quickly assessed for collapse risk under varying seismic scenarios.

Another scenario where generic fragility curves are particularly useful is in large-scale risk assessments that involve extensive geographic regions or a vast number of structures [10]. In such cases, the application of site-specific fragility curves would be prohibitively time-consuming and resource-intensive [49]. Generic curves offer a practical solution by enabling a uniform approach that, while less accurate, can still guide broad policy decisions and strategic planning. This approach is often utilized in national or regional earthquake preparedness programs, where understanding the overall vulnerability landscape is more critical than the intricacies of individual structure responses [12,136].

In the insurance industry, where the rapid assessment of potential liabilities across numerous properties is required, generic fragility curves serve as efficient tools [99]. They enable insurers to estimate damage probabilities and associated costs quickly, which is crucial for setting premiums and reserves for catastrophic events [57,70,181]. Moreover, in the early stages of urban planning and development, these curves can provide initial guidance on the seismic design requirements necessary for new constructions, based on general site and building types, before more detailed studies are conducted [52,136].

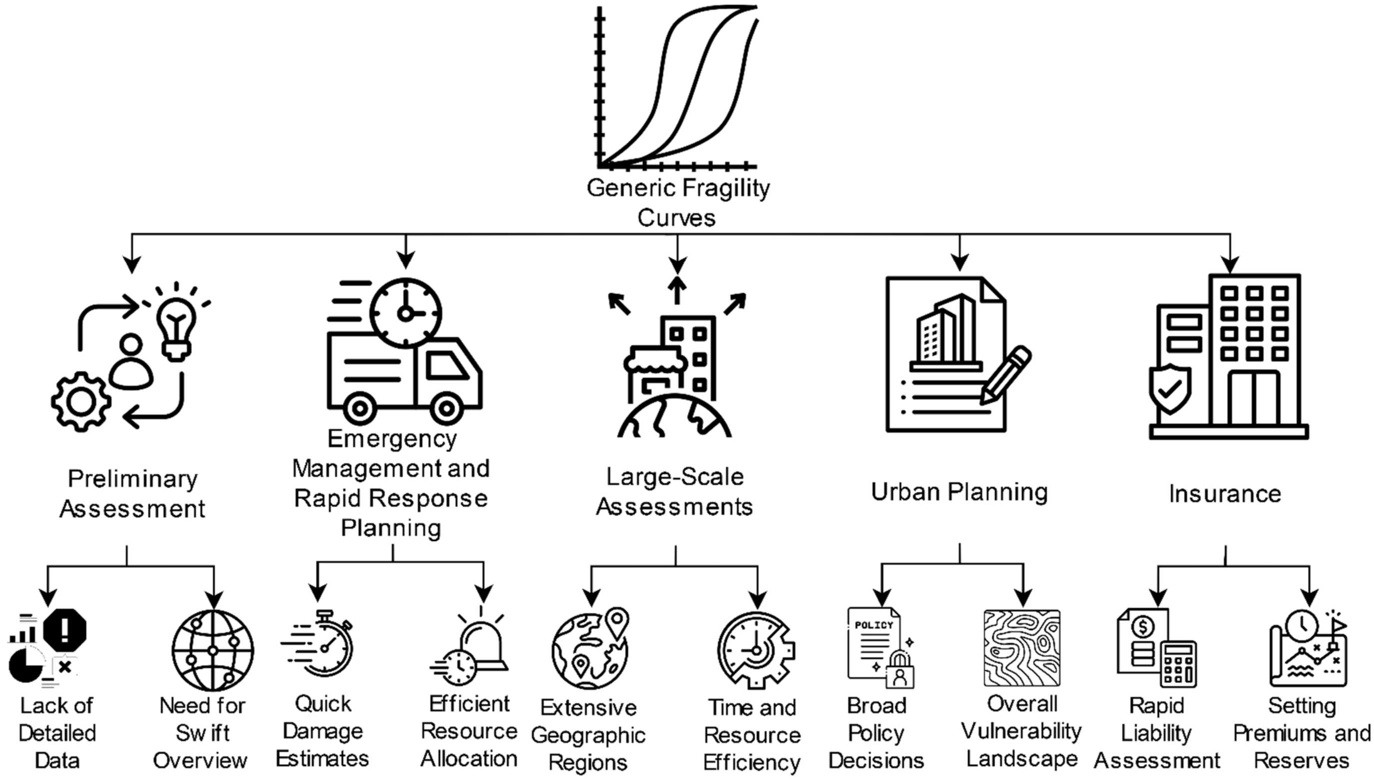

Figure 7. Scenarios preferring generic fragility curves in seismic risk management.

Furthermore, in the field of seismic risk management, the simplicity of generic fragility curves can be beneficial for preliminary screening processes. Hariri-Ardebili and Sattar [182] explore the use of intensified artificial accelerations in fragility assessments, which can be quickly applied in scenarios where site-specific data are lacking. While generic fragility curves may not provide the granular accuracy of site-specific analyses, their utility in scenarios requiring broad overviews, quick decision-making, or large-scale assessments makes them indispensable in the field of seismic risk management [52]. Levine et al. [183] further underline this by showing how generic fragility models are useful for long-term maintenance planning and hazard mitigation across large-scale electrical infrastructure networks. Table 6 outlines scenarios where generic fragility curves are favored in seismic risk management, such as for rapid assessments, data-limited areas, and preliminary evaluations. These provide efficient insights into seismic vulnerability without requiring detailed structural data and are useful for large-scale risk assessments and cost-benefit analysis across various structures and regions.

Table 6. Outlined scenarios where generic fragility curves are preferred in seismic risk management.

Scenario	Description	Citation
Rapid Assessments	When quick evaluations are necessary for immediate decision making, generic fragility curves offer a swift method to estimate seismic vulnerability.	[109,129]
Data Scarcity	In regions where detailed data about buildings and sites are scarce, generic fragility curves provide a feasible alternative to more detailed assessments.	[130,133]
Preliminary Evaluations	For initial seismic risk screenings and feasibility studies, generic curves help in identifying high-risk areas without needing detailed structural information.	[98,133]
Uniform Hazard Consideration	When the focus is on a uniform hazard across different types of structures and sites, generic fragility curves simplify the analysis by standardizing the variables.	[184,185]

Table 6. *Cont.*

Scenario	Description	Citation
Large-Scale Risk Assessments	For large-scale assessments where the detailed modeling of each structure is impractical, generic curves allow for a broad evaluation of potential impacts.	[102,108]
Emergency Response Planning	In emergency response scenarios where time is critical, generic fragility curves offer a quick method to assess potential building damages and inform response strategies.	[95]
Retrofitting Prioritization	For prioritizing retrofit interventions across a broad range of structures, generic curves provide a standardized measure of vulnerability.	[103,131]
Comparative Studies	When comparing different structural types or geographic regions, generic fragility curves offer a baseline for consistent comparisons.	[97,110]
Cost–Benefit Analysis	For evaluating the cost-effectiveness of seismic mitigation measures, generic curves provide a straightforward method to estimate potential benefits relative to costs.	[41,186]
Development of Seismic Codes	In the development and updating of seismic design codes, generic fragility curves help in establishing baseline requirements that apply broadly across different regions.	[99,100]
Insurance and Financial Risk Analysis	For insurance purposes, where assessing the financial risk across a portfolio of properties is necessary, generic curves offer a consistent method for estimating potential losses.	[96,98]
Educational and Training Purposes	For educational purposes and training simulations, generic fragility curves provide simplified models that are easier to understand and apply.	[101,104]
Integration into Multi-Hazard Models	For multi-hazard risk assessments that integrate earthquake risk with other natural hazards, generic fragility curves provide a component that can be easily combined with other risk models.	[184,187]
Seismic Retrofit Cost Estimation	To estimate the costs and benefits of seismic retrofitting across a wide range of buildings, generic fragility curves offer a practical approach for initial calculations.	[27,188]

4.1. RQ2.a. What Are the Inherent Benefits of Using Generic Fragility Curves on a Large Scale?

Generic fragility curves serve as an essential tool in large-scale seismic risk assessments due to their ability to offer rapid and broad evaluations of earthquake vulnerabilities [3]. As shown in Figure 8, generic fragility curves offer significant benefits for large-scale seismic risk assessments. This capability is important, especially for high-level planning and decision-making where a swift understanding of potential risks is necessary across extensive geographic areas. The broad applicability of these curves allows for preliminary assessments that are both quick and economical, reducing the need for immediate, detailed seismic data, which can often be costly and time-consuming to gather [70,136].

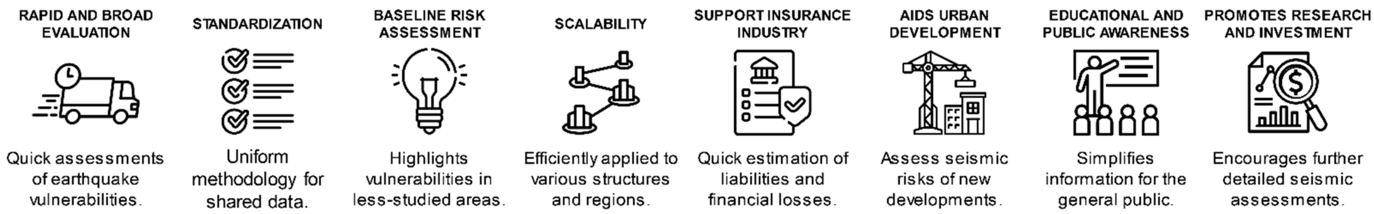

Figure 8. Inherent benefits of using generic fragility curves in large-scale seismic risk assessments.

One of the primary inherent benefits of generic fragility curves is their ability to standardize seismic risk assessments. Stakeholders from various sectors, including government agencies, emergency responders, and urban planners, can easily share and compare data by using a uniform methodology [52,181]. This standardization promotes better communication and coordination, fostering a more unified approach to developing risk mitigation strategies and emergency response plans. For example, during a seismic event, having a standardized approach allows for a more streamlined and effective deployment of emergency services and resources, improving the overall response to disasters [12,65,141].

Generic fragility curves have been shown to offer valuable insights into seismic vulnerability for a range of structure types, including arch bridges [189], thereby enhancing planning and resource allocation.

Moreover, the use of generic fragility curves aids in mobilizing resources and attention towards seismic risk mitigation, especially in less-studied areas. These curves provide a baseline level of risk awareness, which is crucial for regions where specific seismic data may be lacking. By highlighting potential vulnerabilities in these less-analyzed regions, generic fragility curves encourage further research and investment in detailed seismic assessments. This is particularly beneficial for developing countries or rural areas that might not have the infrastructure or funding to conduct detailed site-specific studies initially. For instance, the application of fragility curves in high-risk flood-prone areas is becoming increasingly common for both seismic and other natural hazards, as seen in flood vulnerability studies of bridges in Gujarat, India [190].

Another significant advantage is the scalability of generic fragility curves [49]. They can be efficiently applied to a wide range of structures and regions, making them particularly useful for governmental bodies tasked with national risk assessment and management [65,66]. This scalability also extends to the insurance industry, where companies need to estimate potential liabilities and financial losses from earthquakes swiftly [20,53]. Generic fragility curves allow insurers to perform these estimates without the need for detailed structural analyses of each property, facilitating the calculation of risk premiums and coverage strategies efficiently [181].

Furthermore, generic fragility curves are valuable during the early stages of urban development and land-use planning. They allow planners and developers to assess the overall seismic risk of new developments quickly and make informed decisions about the types and extents of seismic safeguards that should be incorporated [3]. This initial assessment helps in ensuring that new constructions adhere to a basic standard of earthquake resilience, which is vital for promoting safety and sustainability in growing urban environments [191,192]. This methodology can be particularly effective in cases where rapid evaluations of large stocks of similar structures, such as precast buildings, are needed, as demonstrated by Bovo and Savoia [193] in their study on the fast seismic assessment of precast structures.

Additionally, generic fragility curves are crucial in educational and public awareness campaigns [194]. They simplify the complex information associated with seismic risks, making it more accessible to the general public [65,70]. This simplification is important for enhancing community preparedness and resilience [11], as it empowers residents with the knowledge to take proactive steps in preparing for potential seismic events [70,139,141]. Similarly, the development of tools such as the online platform for bridge-specific fragility analysis presented by Stefanidou et al. [195] facilitates both educational and practical applications of fragility curves, making them more accessible for users in various sectors.

Despite their broad applicability and ease of use, it is crucial to note that generic fragility curves are not without limitations [49]. Their generalized nature means they might not capture the unique characteristics of specific sites or buildings, potentially leading to under or overestimations of actual risks [12,66]. Therefore, while they are extremely useful for initial assessments and large-scale analyses, they should ideally be supplemented with more detailed, site-specific studies where possible.

Generic fragility curves provide a range of benefits for large-scale seismic risk assessments, as highlighted in Table 7. Their ability to deliver quick and economical evaluations across broad areas, coupled with their standardization and scalability, makes them an essential tool in the arsenal of earthquake preparedness and disaster risk reduction strategies. These curves lay the groundwork for more detailed investigations and interventions, ensuring that both public safety and economic stability are maintained in the face of seismic threats.

Table 7. Benefits of using generic fragility curves in large-scale seismic risk assessments.

Benefit	Description	Citation
Baseline for Comparative Risk	Provides a consistent baseline for comparing seismic risks across different regions and building types.	[103]
Foundation for Further Research	Provides a foundational tool for subsequent detailed studies and refinement into site-specific analyses.	[110,196]
Support for Policy Making	Assists policy makers in developing broad-based seismic mitigation strategies and building codes.	[128,195]
Public Awareness	Enhances public awareness and understanding of seismic risks in different areas.	[186,197]
Benchmark for Technological Innovations	Serves as a benchmark for evaluating the effectiveness of new seismic technologies and retrofitting techniques.	[185]
Adaptability to Climate Change	Can be adapted to account for changing climatic conditions and their impact on seismic risk.	[105,198]

4.2. Cost-Effectiveness of Generic Fragility Curves in Seismic Risk Management

Generic fragility curves are often favored for their cost-effectiveness compared to site-specific fragility curves. Generic fragility curves, which are derived from a broad dataset and do not account for unique building and site characteristics, provide a practical alternative for large-scale assessments and preliminary evaluations. This cost efficiency stems from several factors, including reduced data collection requirements, simplified analytical procedures, and faster processing times.

Site-specific fragility curves necessitate detailed data on each building's structural characteristics and the local geotechnical conditions, which can be time-consuming and expensive to gather. For instance, Kassem et al. [199] demonstrated that detailed ground motion directionality studies for site-specific risk assessments require extensive computational resources and data collection to analyze directional effects on reinforced concrete buildings. In contrast, generic fragility curves utilize generalized data, significantly cutting down on the need for extensive field surveys and in-depth structural analysis [109,129].

The development of site-specific fragility curves involves complex modeling and simulations tailored to the unique attributes of each site, often requiring advanced software and specialized expertise. Dey et al. [200] explored the use of multi-fidelity approaches that integrate simplified and detailed models for fault rupture displacements in pipelines, emphasizing the high computational demand involved in site-specific assessments. Generic fragility curves, however, rely on established statistical models that can be applied uniformly across different regions, reducing the need for specialized computational resources [130,133]. Because generic fragility curves do not need detailed site-specific input, they enable quicker seismic risk assessments. This is particularly advantageous in emergency response scenarios where rapid decision-making is crucial. The ability to quickly generate risk estimates allows for the timely allocation of resources and implementation of mitigation measures [91,95]. Moreover, Falcone et al. [201] highlighted that using fragility curves in seismic retrofitting cost estimation provided an efficient method to forecast costs based on experimental data, emphasizing that generic curves offer a time- and cost-saving approach, especially in urgent retrofitting assessments.

5. RQ3. How Do Practitioners Balance the Simplicity and Broader Applicability of Generic Fragility Curves with the Need for Precise Risk Assessments in Critical Infrastructure?

Balancing the simplicity and broad applicability of generic fragility curves with the need for accurate risk assessments in critical infrastructure involves a refined approach that integrates both generic (general) and specific assessment strategies. Generic fragility curves, while less detailed, provide a broad overview of potential seismic vulnerabilities, making them particularly useful for initial evaluations across extensive geographic areas or large portfolios of structures. This broad applicability is important in situations where quick decision-making is necessary or where resources for detailed evaluations are limited. Figure 9 illustrates how practitioners balance the simplicity and broad applicability of generic fragility curves with the need for precise risk assessments. This approach allows for rapid, broad evaluations to identify vulnerable facilities, while also enabling adjustments based on localized parameters and updated seismic data as more detailed information becomes available.

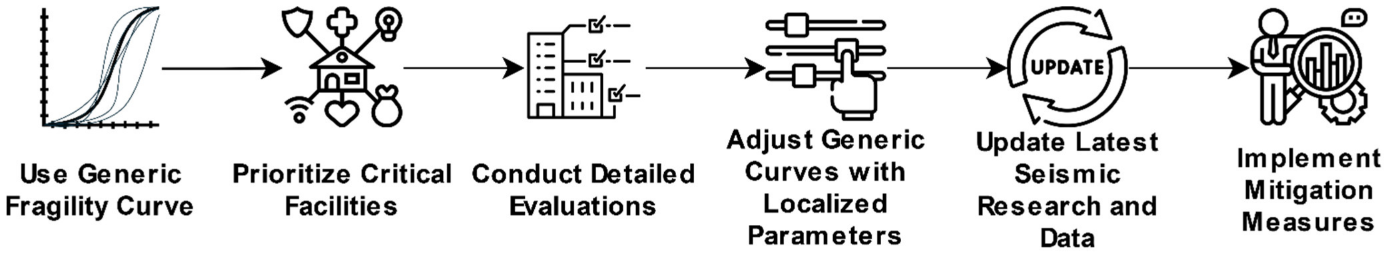

Figure 9. Balance between the simplicity and broad applicability of generic fragility curves with the need for precise risk assessments.

Practitioners begin by employing generic fragility curves to perform a sweeping assessment of all infrastructures within a given area. This initial screening helps to quickly identify facilities that, due to their importance or function, such as hospitals, power plants, and transportation hubs, may require more focused attention. These critical facilities often have a higher impact on societal functions and disaster recovery and thus merit a more detailed analysis [11,70]. The use of generic curves in this context allows for the efficient allocation of resources by narrowing down the list of priorities for further, more detailed evaluation. As shown in Al Jamal et al. [154], using different fragility analysis methods on critical structures highlights how preliminary evaluations can reveal variations in structural vulnerabilities, informing subsequent focused assessments.

Once critical infrastructure is identified, practitioners generally shift towards more detailed, site-specific analyses. These analyses are essential for facilities where failure could lead to significant societal disruption or economic loss [50,65]. Detailed evaluations involve collecting specific data related to the building's design, materials, usage, and local seismic activity—factors that significantly influence a structure's vulnerability to earthquakes [141,202]. This site-specific data overlays the initial assessments from generic curves, providing a layered understanding of risk that helps in accurately pinpointing where mitigation efforts such as retrofitting or strengthening should be concentrated. For example, Cardinali et al. [203] developed a hybrid approach for assessing seismic vulnerability in masonry buildings, demonstrating the importance of combining urban-scale cognitive research with building-level probabilistic procedures to derive fragility curves for detailed risk evaluations.

To bridge the gap between the broad-brush approach of generic curves and the detailed focus of site-specific analysis, practitioners sometimes adopt hybrid approaches. These methods adjust generic fragility curves by incorporating additional parameters that reflect localized conditions, such as soil type, historical seismicity, and specific structural modifications. While these adjusted curves do not offer the full detail of a completely site-specific analysis, they improve the accuracy of the assessments significantly compared to standard generic curves. This method is particularly valuable when full site-specific assessments are not feasible due to budget or time constraints [49,61]. Dhulipala et al. [204], for instance, emphasized the importance of periodic re-evaluations of seismic risks at nuclear facilities, combining baseline generic assessments with updates to reflect evolving hazards, ensuring more precise risk evaluations for critical infrastructures.

Moreover, this balancing act also involves continuously updating both the generic and specific approaches with the latest seismic research and data. The dynamic nature of seismic risk, with new data and predictive models continually developing, requires that both types of fragility curves evolve. Keeping these assessments up to date ensures that the infrastructure is evaluated against the most current understanding of seismic hazards, enhancing the overall reliability of the risk assessments [12,52]. Hancilar et al. [205] demonstrated this need for adaptation by comparing earthquake loss estimations for buildings in Istanbul, showing how fragility models evolve and can be adjusted for better accuracy over time.

Furthermore, practitioners also need to consider the economic implications of their assessments. While detailed site-specific analyses provide the most accurate information, they are also cost-intensive [10]. Here, the use of generic curves can strategically direct limited resources by identifying only those critical areas that truly require the more expensive detailed analysis. This strategy not only optimizes financial expenditure but also ensures that funds are allocated to enhance resilience where it is most needed.

The effective use of generic fragility curves in combination with site-specific analysis requires a strategic and adaptive approach. By starting with a broad assessment using generic curves and honing in on critical areas with detailed analyses, practitioners can efficiently manage seismic risks across large networks of infrastructure. This tiered approach maximizes both public safety and resource allocation, ensuring that critical infrastructures receive the necessary attention to mitigate seismic risks effectively, thereby safeguarding essential services and economic stability in earthquake-prone regions.

6. Conclusions

This review aimed to enhance the understanding of fragility curves, with a specific focus on the differences between building- and site-specific and generic fragility curves in seismic risk assessments. The analysis revealed that building- and site-specific fragility curves, developed through PSHA-based record selection, offer a more accurate representation of seismic demand on structures, allowing for a more effective prioritization of mitigation strategies. These curves provide superior precision and reliability by incorporating local seismic conditions, soil properties, and structural characteristics, enabling more informed decision-making for a variety of structural types. The second key finding demonstrated the inherent benefits of using generic fragility curves in large-scale seismic risk assessments, particularly in terms of providing rapid and economical evaluations across broad areas. These curves are highly useful for standardizing seismic risk assessments, which is essential for emergency response and policy making. The third finding showed how practitioners balance the simplicity and broader applicability of generic fragility curves with the need for precise risk assessments in critical infrastructures. Practitioners can efficiently manage seismic risks across large networks of infrastructure by integrating both generic and specific assessment strategies, optimizing the allocation of resources for mitigation and retrofitting.

The limitations of this review are primarily related to its scope, which includes only academic publications, excluding potentially relevant books, manuals, and other references. Additionally, the rapid advancement of technologies and methodologies may outpace some of the findings presented in this review, highlighting the need for ongoing research to update and expand the understanding of fragility curves and their applications.

This review contributes to the body of knowledge by systematically investigating the literature on fragility curves and offering a clear comparison of site-specific and generic fragility approaches. Future research will focus on real-world applications of these methodologies, with a particular emphasis on integrating multiple hazard types (e.g., tsunamis, flooding) into fragility curve development. Additionally, we recommend exploring advanced numerical simulation techniques for improving fragility models and expanding research across different structural types and regions to enhance the generalizability of the findings.

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